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(54) LIGHT BEAM POLARIZATION MODULATOR

(71) We, WESTINGHOUSE ELECTRIC CORPORATION of Westinghouse Building, Gateway Center, Pittsburgh, Pennsylvania, United States of America, a company organised and existing under the laws of the Commonwealth of Pennsylvania, United States of America, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

The invention relates to improvements in a light modulation system for polarized light.

In United Kingdom patent 1,066,612 there is disclosed and claimed a light modulation system for electronically controlling the passage of polarized light. The modulation system is there disclosed as applied to the resonant optical cavity of a stimulated emission of radiation device as well as to a simple light valve or shutter.

That system has gone into very wide usage because of its capability of very high frequency operation and its capability of operating at what is considered in the art as relatively low modulation voltages. In both, that system and in the system of the present application, the light modulation is effected by direct polarization modulation. In the system which is disclosed in United Kingdom Patent 1,066,612, the type and/or degree of polarization must be known in order to make the proper adjustments to make the system effective. In our copending application No. 32519/71 (Serial No. 1363143) there is described and claimed a light modulation system for modulating light which system is independent of the polarization of the incident light. In other words, the system of the copending application is capable of modulating light energy having random polarization. The electro-optical modulator component of that system may be identical with that of the system disclosed in United Kingdom Patent 1,066,612 as the improvement there resides in combining with the electro-optical crystals of the modulator a birefringent crystal, similar to the birefringent crystal of this invention between the incident light and the first electro-optical crystal. The birefringent crystal resolves any incident light into two orthogonal components and simultaneously produces a lateral displacement between the orthogonal components to produce two parallel light beams which pass through the electro-optical components. In the copending patent application the incident beam may be randomly polarized but in the system of United Kingdom Patent 1,066,612 and as in the present system the incident light beam must be polarized either linearly, circularly or elliptically.

The single light path of the system disclosed in United Kingdom Patent 1,066,612 and the two light paths of the copending application each have two electro-optical crystals in series for the purpose of cancelling any natural birefringence, however, each crystal operates, respectively, on only one of the orthogonal polarization components; passage of an orthogonal polarization component through a crystal which does not operate on that particular component represents an unnecessary attenuation of the light beam.

The object of the present invention is to provide a means for reducing the optical transmission losses in a polarized light modulation system of the types disclosed in applicant's aforementioned patent and copending patent application.

With this object in view the invention resides in a light modulation system for a source of polarized light characterized by means for receiving an incident light beam having plane, circular or elliptical polarization to resolve said light beam into two orthogonally polarized components in

spaced parallel light paths, first and second uniaxial birefringent electro-optical crystals arranged respectively in said spaced parallel light paths; means for applying an electrical field across said uniaxial birefringent electro-optical crystals to vary the index of refraction of the crystals thereby modulating the phase of the two polarized components, and a half-wave plate arranged across said light paths for transmitting the parallel light beam components proceeding from said crystals.

The invention will become more readily apparent from the following description of a preferred embodiment thereof shown by way of example, in the accompanying drawings, in which:

Figure 1 is a schematic illustration for the purpose of explaining the invention;

Fig. 2 is a diagrammatic illustration for the purpose of explaining the invention; and

Figs. 3 and 4 are cross-sectional elevational views of Fig. 2 at the respective sections indicated and looking in the direction indicated by the arrows for two respective conditions and positions of the light vectors as they progress through the modulator from left to right in Figures 1 and 2.

Briefly, the present invention provides an improved electro-optical light modulation system which may be used as a light valve, in general, and specifically as a light modulating device. The system is capable of effecting continuous variation in the transmission of light or effecting pulse modulation thereof. The system is capable of operating at very high speeds in the manner of an "on-off" switch to abruptly cut-off, or on, light energy reflected back and forth in the resonant optical cavity of a stimulated emission of radiation amplifier or oscillator.

An illustrative embodiment of the present invention utilizes the components of a modulation system described and claimed in United Kingdom Patent 1,066,612 in combination with double refracting birefringent crystals and suitable means such as a half-wave plate, to provide two optical transmission paths of equal optical path length for selected portions of the light energy and to thereby reduce the transmission losses for light energy having a selected polarization. Whereas the system of applicant's copending patent application is adapted to control light energy of any polarization, the present invention contemplates an improved electro-optical system in which the optical transmission losses, or the modulation voltage, are reduced by a factor of two when the polarization of the light energy is known.

Referring to Fig. 1 there is shown an embodiment of the present invention wherein the system is to be used where it is merely desired to modulate the polarization of a light beam passing in a single direction. A later embodiment is described in which the system is designed to control the light energy in a multi-reflected path.

The essence of the present invention resides in the association of birefringent crystals, such as crysals 2 and 3, having characteristics well known but not heretofore used in the combination disclosed herein and in the use of a half wave plate across both light paths in conjunction with the birefringent crystals to obtain equal optical path lengths through the modulator (zero retardation) for both orthogonal polarization components of the incident light.

In optical modulation systems of the type under consideration here, uniaxial electro-optical crystals are commonly used to polarization modulate light beams. Specific preferred examples are the dihydrogen phosphate type, such as potassium dihydrogen phosphate (KDP). These crystals, which are normally uniaxial, become biaxial when an electric field is applied along one of the principal optic axes. Such crystals have one axis, namely, the Z axis, along which the index of refraction is not altered by an applied voltage. The electro-optic effect is the result of changes in the index of refraction which occur along the other axes X and Y when a modulating electric field is applied along the Z axis.

Still referring to Figure 1, an incident light beam indicated at 1, for example from a laser, linearly polarized as indicated by the vector 6, i.e. at 45° with respect to the axes of the birefringent crystal 2, will be doubly refracted by the crystal 2 to give two orthogonal components in the light paths 7 and 8. The axis of component 7 will be displaced in a direction normal to the axis of the incident light beam 1 by an amount which is a function of the birefringence and length of the crystal 2. Thus, the crystal 2 resolves the linearly polarized beam 1 into two laterally spaced orthogonal components in two respective parallel optical paths. The light energy of the light paths 7 and 8 may be passed through an optical phase modulating device 4 which includes electro-optical crystals 10 and 11 arranged to impart a phase retardation in the paths 7 and 8, respectively. Respective induced X and Y axes of each of the crystals 10 and 11, for example the X axis of crystal 10 and the Y axis of crystal 11, are oriented parallel to the planes of polarization of the orthogonal component of the associated input beams and the other axes X and Y are oriented parallel to the path of the light beam. The light energy emerging from the phase modulator 4 along paths 7 and 8 can be combined into a single emergent light beam having the same polarization as the incident beam by means of a half wave plate 9 and a crystal 3 which has the same characteristics as that of crystal 2 and performs the inverse

of the operation performed by crystal 2. The half wave plate 9 is used to equalize the optical path lengths for the paths 7 and 8 in order to obtain zero retardation at zero modulation voltage. This equalization is obtained by converting the vertically polarized component into a horizontally polarized component and the horizontally polarized component into a vertically polarized component. As a result, the recombination which takes place in the birefringent crystal 3 introduces a supplementary path length on the light beam which has not been deviated in the crystal 2.

By applying a modulation voltage to crystals 10 and 11, sufficient to produce a 180° phase shift between the polarization vectors 13 and 14 of the light along paths 7 and 8, the emergent vector 6′ can be effectively rotated 90° with respect to incident vector 6.

When the present invention is being used as a light modulator or light shutter, as illustrated in Figure 1 of the drawings, the emergent beam 1′ is directed through an appropriate analyzer 12 to effect intensity modulation of the light beam. The intensity modulation is effected by polarization modulation of the resultant emergent light vector 6′ relative to the plane of polarization of the analyzer.

In the polarized light system of United Kingdom patent 1,066,612 and in the randomly polarized light system of said copending application, both orthogonal components of the light energy must pass through both of the electro-optical crystals in series. In the present invention only one-half of the light energy, that is the light energy in the component to be operated upon, passes through one electro-optical crystal and the other half passes through the other crystal resulting in a reduction of the optical transmission losses for the system by a factor of two as compared to the system of United Kingdom patent 1,066,612 and that of the copending patent application.

Referring again to detailed description of the invention, the crystals 2 and 3 serve as means for generating, separating and recombining, respectively, the orthogonal components of the energy in the light beam 1, the plane of polarization of which is indicated by the vector 6. In order to obtain sufficient spatial separation to carry out the objectives of the invention and have one of the components pass through one of the electro-optical crystals 10 while the other one passes through the electro-optical crystal 11, it is necessary to choose the proper material for the crystals 2 and 3. Furthermore, the crystal geometry must be optimized by carefully orienting the incident light beam with respect to the optic axis of the said crystals. This requirement for the present invention is substantially the same in this respect as for the system in said copending application and it has been found that a biaxial crystal which gives an angle separation of approximately 9.5° for a light beam having a wavelength in the neighborhood of from 4000 to 15,000 Angstroms can provide sufficient separation within the practical limits of the crystal to carry out the objectives of the invention. The separation of the orthogonal components of the light beam, illustrated in Fig. 2 and Fig 3, indicates that the light beam 1 which is shown polarized at 45° with respect to the horizontal and vertical axes is resolved into two orthogonal components, one of which is the ordinary ray (O ray) which is horizontal and indicated by the vector 14. The other is the extraordinary ray (E ray) which is vertical and indicated by the vector 13.

From Figs. 2 and 3 it will be seen that with the physical axis of the crystal 2 properly oriented with respect to the incident light beam 1 the ordinary ray O will not be deviated as it passes through the crystal 2 but it will contain the horizontal component indicated by the vector 14. The ordinary ray O will coincide with the optical axis of path 8 through the electro-optical crystal 11. The extraordinary ray E will emerge parallel to the ordinary ray O (path 8) and will follow the path 7. The deviation of the extraordinary ray E to make it parallel to the ordinary ray O is caused by the biaxial crystal 2 by virtue of its double refractive properties.

The extraordinary ray E and the ordinary ray O will emerge from the right-hand side of the electro-optical crystals 10 and 11, respectively, parallel to each other and pass through the half wave plate 9. The half wave plate 9 effectively rotates the plane of polarization of the E and O rays to make the emergent rays O′ and E′, respectively, with respect to crystal 3 as illustrated in Figure 4. The emergent rays O′ and E′ are then recombined in crystal 3, inverse to the manner in which separation of the rays was obtained in crystal 2 and emerge as an output light beam indicated at 1′.

Assuming that there is no energization of the electro-optical phase modulator 4, the electric vectors 13 of the extraordinary ray E and the vector 14 of the extraordinary ray O will remain in the same relative positions that they are shown in Fig. 3, being orthogonal. Both of the rays E and O will pass straight through the crystals 10 and 11, respectively, without any additional lateral axis deviation. As the extraordinary ray E′ enters the crystal 3 it will be deviated back to the optical axis of the ordinary ray O′ and the output beam represented at 1′ will have the same polarization as the incident beam represented by the vector 6 which is

at 45° with respect to the horizontal and vertical axes.

Now assume that the electro-optical phase modulator 4 is energized, that is, it is in what may be called the closed position as far as the light valve action is concerned. The incident light beam will be split into the two spaced rays E and O with paths spaced as indicated in Figs. 1 and 2. The linear polarization of the incident beam 1 will be resolved into two orthogonal components, one of which will be the extraordinary ray E along path 7 as being vertical and the other will be the ordinary ray O along path 8 and this component will be horizontal. As the two rays pass through the electro-optical phase modulator 4 the phase difference between the E and O rays will be modified to an extent dependent upon the magnitude of the applied modulating voltage. Upon recombining the O′ and E′ rays in crystal 3, the resultant 6′ will be polarization modulated. For an induced phase difference of 180° between the E and O rays, the polarization of the resultant 6′ will be orthogonal to the polarization of the incident beam 6. Therefore, light valve action can be obtained by placing an analyzer (in Fig. 2) in the emergent light beam 1′, with the analyzer 12 in Fig. 1, not shown in Fig. 2, having its polarization vector orthogonal to the plane of polarization of the original beam 6.

Fig. 2 shows the manner in which the voltage is applied between terminal 26 and ground 27. The voltages are applied in parallel to the electro-optical crystals 10 and 11 along the Z axes which are orthogonal with respect to each other.

Preferably although not necessarily, the elongated electro-optical crystals 10 and 11 may have a square cross section. They may have a rectangular cross section, so long as the dimensions along the respective Z axes are the same. The physical axis of respective rods should be the 100 and 010 axis (X and Y axis) (according to the Miller system of notation of the faces and internal planes of a crystal).

Since there are two separated linearly polarized orthogonal beams which are acted upon separately by the phase modulator 4, it is important that the geometry of the electro-optical crystals 10 and 11 be such that the extraordinary ray E and the ordinary ray O be absolutely parallel to one of the principal optic axes of the respective crystals.

The theory of operation of applying the potential across the crystals 10 and 11 is to be found in British Patent Specification 1066612.

Since the incident light energy is resolved into two orthogonal components, each of which is restricted to a single light path that includes only a single electro-optical crystal for operating on that particular component the optical transmission losses are reduced by a factor of two over those systems in which both components must pass through both electro-optical crystals in series.

WHAT WE CLAIM IS:—

1. A light modulation system for a source of polarized light characterized by means for receiving an incident light beam having plane, circular or elliptical polarization to resolve said light beam into two orthogonally polarized components in spaced parallel light paths, first and second uniaxial birefringent electro-optical crystals arranged respectively in said spaced parallel light paths; means for applying an electrical field across said uniaxial birefringent electro-optical crystals to vary the index of refraction of the crystals thereby modulating the phase of the two polarized components, and a half-wave plate arranged across said light paths for transmitting the parallel light beam components proceeding from said crystals.

2. A light modulation system as claimed in claim 1 wherein said means for receiving said incident light beam includes a first birefringent element.

3. A light modulation system as claimed in claim 1 or 2 including means for receiving light from said half-wave plate across said parallel paths and recombining said parallel light beam components into a single polarization modulated light beam substantially collinear with said incident light beam.

4. A light modulation system as claimed in claim 3, including means for converting the polarization modulation of the recombined light beams, the components of which are phase modulated, into intensity modulation of the recombined light beam.

5. A light modulation system as claimed in claim 3 or 4 as dependent on claim 3, wherein said means for recombing said parallel paths into a single light beam includes a second birefringent element having substantially the same characteristics as said first birefringent element of said means for receiving said incident light beam.

6. A light modulation system as claimed in any one of the preceding claims wherein said uniaxial birefringent electro-optical crystals have substantially the same index of refraction and the same length and each have substantially identical mutually orthogonal first, second and third axes, the third axes being the unique optic axes and being mutually orthogonal and disposed perpendicular to the axis of said parallel light paths, the first and second axes being the semi-axes of the refractive index ellipsoid induced on application of an electric field, the first axis of one crystal being parallel with the second axis of the other crystal,

and parallel to said parallel light paths, and the second axis of the one crystal and the first axis of the other crystal being parallel to the electric vector of the respective orthogonal component of the light beam passing therethrough, and said electrical field being applied along said third optic axes.

7. A light modulation system as claimed in claim 2 or any of the claims 3 to 6 as dependent on claim 2 wherein at least said first birefringent element is so disposed about the axis of said incident beam that the respective optic axes thereof are disposed at 45° with respect to the electric vector of said incident beam.

8. A light modulation system as claimed in any one of the preceding claims including means for providing said incident light beam from stimulated emission of radiation.

9. A light modulation system for a source of polarized light substantially as hereinbefore described with reference to the accompanying drawings.

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1,363,885 COMPLETE SPECIFICATION
1 SHEET
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